II. MODELING OVERVIEW

A. FROUDE HYPOTHESIS

By Froude's hypothesis, the total resistance coefficient C_T is a function of Reynolds Number Rn and Froude Number Fn. Additionally, the total resistance coefficient may be divided into frictional and residual components. The frictional resistance coefficient C_F is a function of Reynolds Number only while the residual resistance coefficient C_R depends on both the Reynolds Number and Froude Number.

$$C_T(Rn, Fn) = C_F(Rn) + C_R(Rn, Fn) \qquad (1)$$

A further subdivision of the residual resistance coefficient is possible by understanding that the wave making resistance coefficient C_{WM} is included in the residual resistance coefficient. What remains of the residual resistance coefficient is the form drag coefficient C_{FORM}. The wave making resistance coefficient is a function of the Froude Number only and the form drag coefficient is constant for geometrically similar hulls.

$$C_R(Fn) = C_{WM}(Fn) + C_{FORM} \qquad (2)$$

Therefore, the total resistance coefficient is given by the following equation.

$$C_T(R_n, F_n) = C_F(R_n) + C_R(F_n) + C_A \qquad (3)$$

A correlation allowance C_A is added to the ship frictional and ship residual coefficients to give the ship total resistance coefficient. Figure 2.1 shows a general division of the model and ship resistance coefficients.

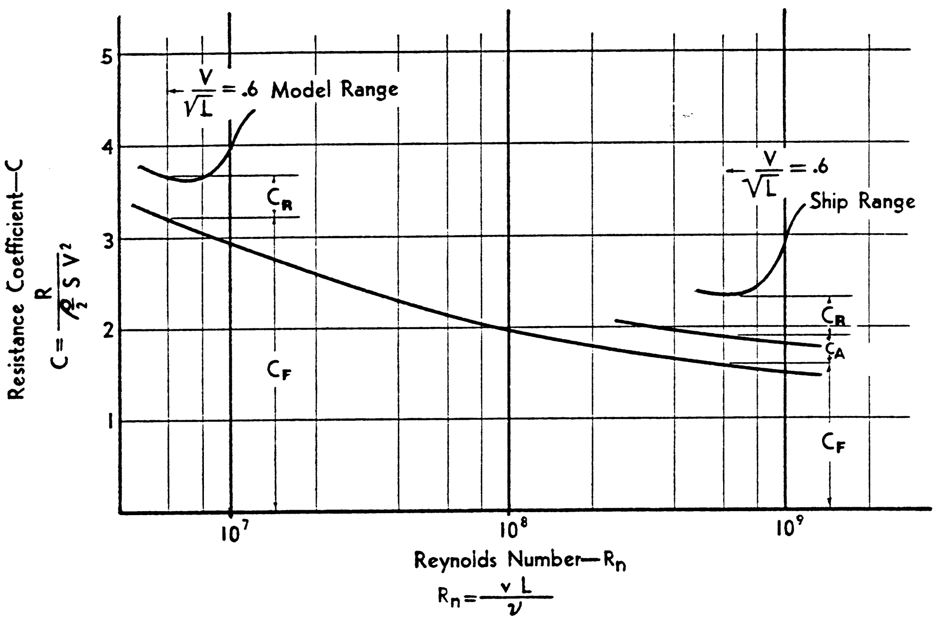


Figure 2.1. Model and ship resistance coefficients versus Reynolds Number (Gilmer and Johnson, 1982).

B. ITTC METHOD

The ITTC Method follows Froude's hypothesis for the total resistance coefficient. It proposes an equation that produces a curve on the resistance coefficient C_F versus Reynolds Number plot which represents the portion of the total coefficient due to friction as

$$C_F = \frac{0.075}{\left(\log_{10} Rn - 2\right)^2} \tag{4}$$

The ITTC method maintains the concept that the residual resistance coefficient is comprised of the wave making resistance and form drag components. The wave making resistance coefficient is dependent upon the Froude Number. For Froude scaling, the model and ship have the same Froude Numbers. Therefore, for a given Froude Number the model wave making resistance coefficient is equal to the ship wave making coefficient. Since the form drag coefficient is constant for geometrically similar vessels, the wave making and form drag coefficients can be analyzed at each Froude Number as a constant sum known as the residual resistance coefficient.

$$C_R\left(Rn, Fn\right) = C_{WM}\left(Fn\right) + C_{FORM} \tag{5}$$

In this way, an estimate of the ship total resistance coefficient may be derived from model test tank measurements. The component breakdown of the total resistance coefficient for the ITTC method is shown in Figure 2.2. In summary, the total resistance coefficient for the ITTC method is given by the following equation.

$$C_T\left(Rn, Fn\right) = C_F\left(Rn\right) + C_R\left(Rn, Fn\right) \tag{6}$$

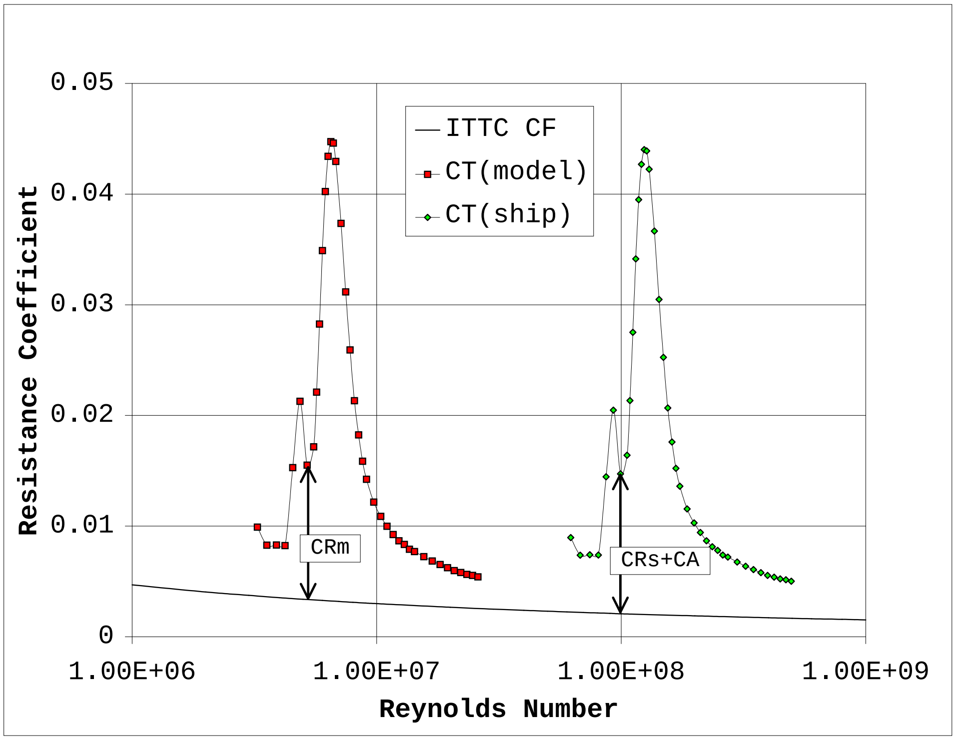


Figure 2.2. Total resistance coefficient versus Reynolds Number for an ITTC analysis.

C. HUGHES METHOD

The Hughes method suggests a variation on Froude's hypothesis and modifies the friction coefficient curve. The analysis suggests that the frictional resistance and form drag are due to viscous effects and are therefore both a function of Reynolds Number. As plotted on Figure 2.3, the Hughes curve equation for the frictional resistance coefficient C_{FO} is

$$C_{FO} = \frac{0.066}{\left(\log_{10} Rn - 2.03\right)^2} \tag{7}$$

The analysis proposes that the form drag coefficient can be related to the frictional resistance coefficient curve by some constant η.

$$C_{FORM}(Rn, Fn) = \eta \; C_{FO}(Rn) \tag{8}$$

By multiplying the frictional resistance coefficient by a form factor r, the form drag and frictional resistance components are combined into a single Reynolds dependent term. At low Froude Numbers the wave making resistance is negligible and therefore at a low speed the following holds:

$$C_T(Rn, Fn) = C_{FO}(Rn) + C_{FORM}(Rn) + \underbrace{C_{WM}(Fn)}_{0} \tag{9}$$

$$C_T(Rn, Fn) = (1 + \eta) C_{FO}(Rn) \tag{10}$$

$$C_T(Rn, Fn) = r \; C_{FO}(Rn) \tag{11}$$

In this way, the form factor may be found for the hull shape. The form factor is constant for geometrically similar hulls. In general, the total resistance coefficient may be written in the form

$$C_T(Rn, Fn) = r \; C_{FO}(Rn) + C_{WM}(Fn) \tag{12}$$

The component breakdown of the total resistance coefficient is shown in Figure 2.3. The residual resistance coefficient for the Hughes method is a function of both the Reynolds Number and the Froude Number.

$$C_R(Rn,Fn) = C_{WM}(Fn) + C_{FORM}(Rn) \tag{13}$$

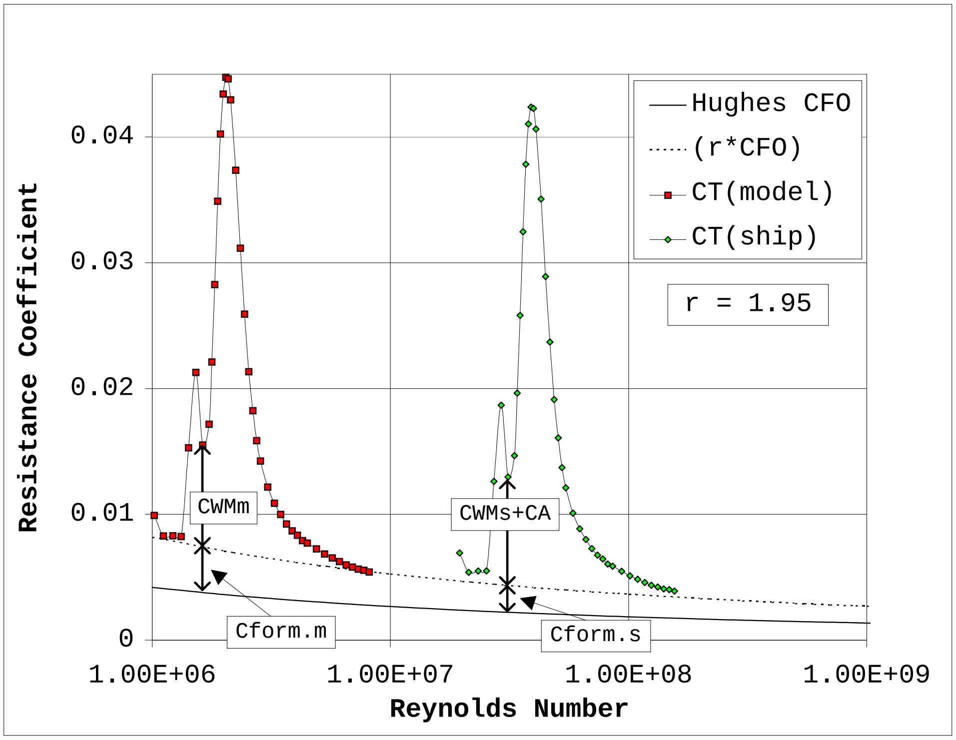
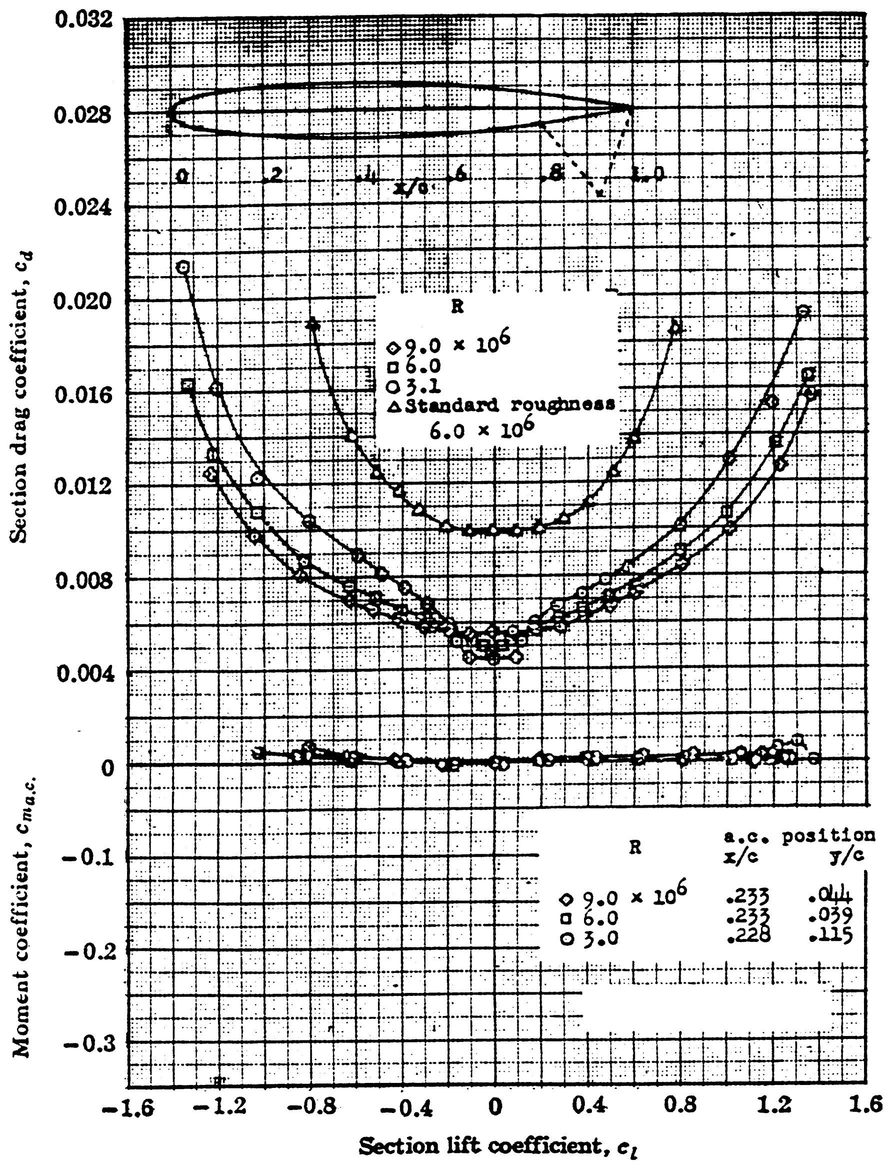


Figure 2.3. Total resistance coefficient versus Reynolds Number for the Hughes analysis.

D. MODIFIED HUGHES METHOD

A further investigation was developed in which the struts were evaluated as wing sections. By this premise, one may consider the total drag attributed to the struts as equivalent to the drag of a geometrically similar wing shape. Using Figure 2.4, a wing drag coefficient $C_{d_{Wing}}$ was extracted.



NACA 0012-64 Wing Section (*Continued*)

Figure 2.4. Section drag coefficient versus section lift coefficient for a NACA 0012-64 wing section (Abbott and von Doenhoff, 1959).

This wing drag coefficient however does not account for the effects of wave making resistance. Therefore, a wave making term must be added to account for its absence.

$$C_{T_{Strut}}\left(Rn,Fn\right)=C_{d_{Wing}}\left(Rn\right)+C_{WM_{Strut}}\left(Fn\right) \tag{14}$$

Applying the Froude analysis to the strut total resistance coefficient, the following may be written for the strut total drag coefficient.

$$C_{T_{Strut}}\left(Rn,Fn\right)=C_{FO_{Strut}}\left(Rn\right)+C_{WM_{Strut}}\left(Fn\right)+C_{FORM_{Strut}} \tag{15}$$

By assuming that at low Froude Numbers, in other words low speeds, the wave making resistance is negligible, the wing drag coefficient is equivalent to the strut total drag coefficient. This allows the strut form drag coefficient to be obtained by subtracting the strut frictional resistance coefficient from the strut total drag coefficient.

Because the wetted surface area was fragmented, the resistances, not the coefficients, were be used to arithmetically account for all effects. Once the portion of the form drag attributed to the struts was known, the pod form drag was calculated by subtracting the strut contribution from the overall form drag found in the Hughes analysis.

$$R_{FORM_{Pod}}=R_{FORM}-R_{FORM_{Strut}} \tag{16}$$

Due to the shape of the pods (oblong / aspect ratio) the form drag coefficient of the pods were considered functions of Reynolds Number and were therefore Reynolds scaled according to the Hughes method. The strut was approximated by a flat plat in turbulent flow with a constant form drag coefficient. Therefore, it is appropriate to separate the strut and pod form coefficients for the model to ship scaling process.

$$C_{FORM_{Pod}}(Rn,Fn) = \eta \; C_{FO_{Equiv}}(Rn) \tag{17}$$

$$C_{FORM_{Strut}} = const \tag{18}$$

The component breakdown of the total resistance coefficient is shown in Figure 2.5. Computationally, the separate resistance coefficients were found from their respective resistances in the following equation.

$$R_T(Rn,Fn) = R_{FO_{Equiv}}(Rn) + R_{FORM_{Pod}}(Rn) + R_{WM}(Fn) + R_{FORM_{Strut}} \tag{19}$$

The residual resistance coefficient for the Hughes method is a function of both the Reynolds Number and the Froude Number and was found from the summed residual resistance.

$$R_R(Rn,Fn) = R_{WM}(Fn) + R_{FORM_{Pod}}(Rn) + R_{FORM_{Strut}} \tag{20}$$

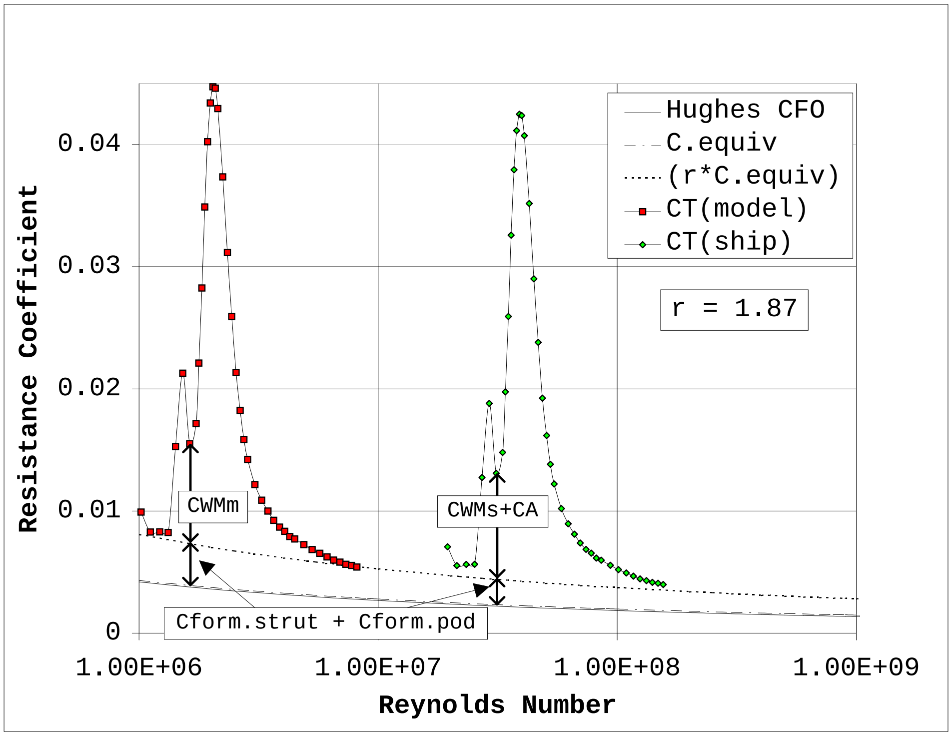


Figure 2.5. Total resistance coefficient versus Reynolds Number for the modified Hughes method.

In essence, the Hughes method has been modified such that the portion of the form drag attributed to the pods was reduced in the transfer from model to ship by Reynolds scaling while the strut portion was Froude scaled. An equivalent Hughes coefficient, found from R_{Equiv}, an equivalent resistance

$$R_{Equiv} = \left(R_{FO} + R_{FORM_{Strut}}\right) \tag{21}$$

was multiplied by the form factor r, to raise this equivalent Hughes curve to the desired value of the total resistance coefficient specified by the Hughes Method. Alternatively, the same form factor would be found by raising the original Hughes curve to a value equal to the total resistance coefficient minus an equivalent strut form drag coefficient.